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C.C. WANG and E.T. KORNHAUSER

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Propagation on Modulated Corrugated Rods*

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Abstract

The velocity of surface-wave propagation on two types of axially modulated corrugated rods has been measured experimentally. Type A has a constant outer diameter and sinusoidally varying slot depth, while in type B the slot depth varies in virtue of a modulated outer diameter. In both cases the measured phase velocity is about ten percent less than that for a uniformly corrugated rod with the average slot depth and outer diameter, but agrees within two percent over the frequency range used with the value calculated from an analysis based on the Mathieu equation.

I. Introduction

Interest in the properties of modulated surface-wave structures stems from their application as end-fire antennas.[1] Further work has indicated the possibility of producing radiation in other desired directions[2], and most recently a technique has been presented for designing the modulations of a plane corrugated surface so as to support several slow waves simultaneously.[3]

The analysis of the radiation characteristics of finite lengths of such structures has been based on the surface-wave propagation properties

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* This work is part of a thesis submitted by one of the authors [C. C. W.] to Brown University for the M.Sc. degree.

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of the infinitely long structure. To that end experiments were performed on two types of corrugated cylinders, which are the most useful configuration for practical application, and their surface-wave phase velocity measured as a function of frequency. The infinitely long structure was simulated by the use of parallel reflecting planes at each end.

Structure A, shown in figure (1), is a cylinder with constant outer diameter of 0.85", whose inner diameter (at the bottom of the slots) varies sinusoidally in the axial direction between 0.4" and 0.85". The average inner diameter is thus 0.625" and the average slot depth 0.1125". The width of each slot is .05", and their spacing is 0.1". The structure was constructed by stacking brass washers of .05" thickness and various diameters on a steel rod 0.2" in diameter with sufficient axial pressure to insure good electrical contact between washers. The axial period of the modulation is 1.2", and the whole structure is about 11" long.

Structure B, shown in figure (2) mounted between its reflecting end plates, was constructed in a similar manner, but had a constant inner diameter of 0.4" and an outer diameter varying sinusoidally over the same 0.4 - 0.85" range. The slot width is the same as in A, but the slot spacing is 0.15", so that the modulation period is 1.8", and the total length is about 14".

II. Experimental Measurements.

The phase velocity of the surface wave propagating on infinite lengths of the two structures described in section I was measured by determining the wavelength of the standing wave on the structures when mounted between parallel reflecting planes. The reflectors were circular aluminum plates, about 18" in diameter, accurately alligned parallel to each other and perpendicular to the axis of the rods by means of the adjustable supports shown in figure (2). The planes were located at either a minimum or maximum slot depth so as to preserve the periodicity of the structure and its image.

Energy from a Varian X-13 reflex klystron was introduced at one end by means of a coaxial line coupled through a small hole in the center of the circular plate. The frequency was varied over a range from about 8.3 to 9.7 kmc. and measured by means of a cavity wavemeter. The wavelength of the resulting standing-wave pattern was determined from the average distance between minima when the structure was in resonance. The minima were located with a loop-type probe mounted on a travelling carriage, as shown in figure (3), so as to traverse a path parallel to and about 3 cm. away from the rod axis.

The results of these measurements as a function of free-space wavelength are shown on figure (4), where it may be seen that they are in good agreement with the results of the analysis to be described in the following section.

III. Analysis.

The theory of uniform corrugated rods has been examined in considerable detail[4,5] and also checked experimentally.[6,7] If one may assume that the corrugations of the structures investigated here vary slowly enough relative to the wavelength, the propagation should be described by an equation of the form

$$\frac{\partial^2 \psi}{\partial z^2} + (\omega/v_p)^2 \psi = 0 , \qquad (1)$$

where v_p is a periodic function of z whose value at any point may be obtained by inserting the inner and outer diameters at that point into the formulae of references (4) or (5). Such a formula for the circularly symmetric TM wave is given as [4]

$$\frac{J_1(\beta_o a)N_o(\beta_o b) - N_1(\beta_o a)J_o(\beta_o b)}{J_o(\beta_o a)N_o(\beta_o b) - N_o(\beta_o a)J_o(\beta_o b)} = \frac{w}{p} \cdot \frac{\beta_o}{\gamma} \cdot \frac{K_1(\gamma a)}{K_o(\gamma a)} , \qquad (2)$$

where $\beta_o = 2\pi/\lambda_o$, a and b are the outer and inner diameters respectively, p is the slot spacing, w is the slot width, $\gamma^2 = \beta^2 - \beta_o^2$, and $\beta = 2\pi/\lambda = \omega/v_p$, where λ is the guide wavelength. Since a or b are sinusoidally varying functions of z in structures A and B , the resulting values of β , and hence $1/v_p^2$, will be periodic functions of z also, although not simply sinusoidal. Let

$$F(z) = 1/v_p^2 = C_o + C_1 \cos \frac{2\pi z}{d} + C_2 \cos \frac{4\pi z}{d} + \ldots , \qquad (3)$$

where d is the axial period of the modulation, so that equation (1) takes the form

$$\frac{\partial^2 \psi}{\partial z^2} + \omega^2 F(z) \psi = 0 , \qquad (4)$$

where $F(z)$ is periodic with period d . Equation (4) is Hill's equation, which reduces to the one-dimensional wave equation when only the first term in (3) is retained and to the Mathieu equation when only the first two terms are retained.

The crudest approximation one can make in equation (4) is to assume $F(z)$ is a constant equal to the value of $1/v_p^2$ at the average value of outer diameter and slot depth. The resulting values of v_p/c were calculated from equation (2) as a function of λ_o and are shown by the dashed curves in figure (4). It may be seen that these curves are about ten percent higher than the experimental points. This discrepancy is not surprising when one considers that the amplitude of the modulation in these rods was quite large and that the minimum value of $v_p(z)$ deviates considerably more from the value for the average diameter than does the maximum, as indicated in figure (5).

The form of $F(z)$ shown in figure (5) suggests that a reasonable fit to $F(z)$ could be made with the first three terms of the Fourier series as in equation (3). An approximate evaluation of the three coefficients C_o, C_1, and C_2 can be made with only the three values of $F(z)$ at its maximum, its minimum, and at a point halfway between them. The equations relating the coefficients to these values are then

$$\begin{aligned} F_{max} &= C_o + C_1 + C_2 \\ F_{1/2} &= C_o - C_2 \\ F_{min} &= C_o - C_1 + C_2 \; , \end{aligned} \tag{5}$$

from which one obtains

$$\begin{aligned} C_o &= \frac{1}{2} F_{1/2} + \frac{1}{4} (F_{max} + F_{min}) \\ C_1 &= \frac{1}{2} (F_{max} - F_{min}) \; . \end{aligned} \tag{6}$$

The approximate curve resulting from the use of these three terms is shown also in figure (5) for the case depicted there. It is of course possible to use C_o as a better average value of $F(z)$ and to calculate the phase velocity for the structure from it, as in the preceeding paragraph, but these values, while closer to the experimental points, are still considerably in error. A better approximation is obtained by retaining the first two terms of the expansion, C_o and C_1, so that equation (4) becomes the Mathieu equation.

If one reduces the periodicity from d to π by letting $\xi = \pi z/d$ and furthermore sets

$$\eta = \omega^2 d^2 \, C_o/\pi^2$$
$$\gamma = \omega^2 d^2 \, C_1/\pi^2 \, , \tag{7}$$

the equation of propagation takes the form

$$\frac{d^2u}{d\xi^2} + (\eta + \gamma \cos 2\xi) \, u = 0 \quad , \tag{8}$$

which is the form of the Mathieu equation as discussed by Brillouin.[8] This equation has solutions of the form

$$u(\xi) = A(\xi) \, \varepsilon^{im\xi} \, , \tag{9}$$

where $A(\xi)$ is a periodic function with period π, and m is the desired propagation constant. For certain ranges of the parameters η and γ the value of m is real, corresponding to unattenuated propagating waves. These regions are indicated by the shaded portions of the $\eta - \gamma$ plane shown in figure (6). The unshaded portions correspond to complex values of m, and for these values of the parameters no propagating wave is possible. The values of m on each of the boundary lines between the pass and stop regions are integers and are indicated on the curves. To find the value of m for points lying within the shaded regions one must interpolate between the integral values on either side of the region, since the computation of m for arbitrary η and γ is too difficult. The values of η and γ for the boundary lines, corresponding to integral m, however, may be obtained from N.B.S. tables[9]. Clearly for small values of γ, m is given simply by $\sqrt{\eta}$, which is also obvious from equation (8). The values of γ involved in the present investigation are, however, in the range from $\eta/2$ to η, and the corresponding deviation of m from $\sqrt{\eta}$ is quite significant.

Having determined the value of m by interpolation from figure (6), one can finally calculate the guide wavelength λ from

$$\lambda = 2d/m \,,$$

and

$$v_p/c = \lambda/\lambda_o = 2d/m\lambda_o \,. \tag{10}$$

The calculations outlined in the preceeding paragraphs have been carried out for two values of λ_o for each of the two structures, and the results are shown in table (I) as well as plotted on figure (4). It may be seen that the final results of this calculation agree with the experimental points to within about two percent over the frequency range in which the calculations were performed. Further refinement is not warrented by the experimental data, and in any case a calculation from Hill's equation using a greater number of terms in the Fourier series for $F(z)$ becomes too difficult.

IV. Conclusions.

From the agreement between the theoretical curve and the experimental points on figure (4) one can conclude that the analysis of these modulated surface-wave structures by means of a Mathieu equation is fairly accurate, in spite of the rather wide slots in these structures, the crudeness of the approximation to $F(z)$, and the fact that d and λ were of the same order of magnitude. One notes, as is to be expected, that the agreement is better in those cases where the modulation is less severe, but even where $F(z)$ varies over a four-to-one range, the result is not greatly in error.

Concerning the properties of modulated corrugated rods in general, one notes that v_p is more nearly independent of frequency than for a uniform rod. The tendency of v_p to decrease with decreasing wavelength is compensated by the fact that C_o moves closer to the minimum of $F(z)$ as the form of $F(z)$ becomes more peaked. On the other hand the effect of increasing the modulation, and hence C_1, for a given C_o, in the range of parameters used here is to decrease m, or increase v_p, but this is not universally true nor is it the dominant effect here. There is also very little difference between structures A and B with respect to dispersion.

Finally with more extensive observation over the possible range of η and γ, one should be able to demonstrate the existence of the stop bands predicted in figure (6), but no such effect was observed in the experiments performed here.

TABLE I

(a) STRUCTURE A, d = 3.05 cm.

λ_o cm.	a cm.	v_p/c	F(z)	C_o $sec^2/cm^2 \times 10^{21}$	C_1	η	Υ	m	λ cm.	v_p/c
	.508	.523	4.06							
3.62	.794	.905	1.36	1.98	1.48	5.06	3.78	2.00	3.05	0.843
	1.08	1.00	1.11							
	.508	.436	5.83							
3.40	.794	.893	1.39	2.43	2.36	7.03	6.84	2.20	2.78	0.818
	1.08	1.00	1.11							

(b) STRUCTURE B, d = 4.57 cm.

λ_o cm.	b cm.	v_p/c	F(z)	C_o $sec^2/cm^2 \times 10^{21}$	C_1	η	Υ	m	λ cm.	v_p/c
	.508	1.00	1.11							
3.625	.794	.929	1.29	1.58	0.75	9.03	4.34	2.97	3.08	0.850
	1.08	.651	2.61							
	.508	1.00	1.11							
3.40	.794	.925	1.30	1.75	1.08	11.38	7.02	3.15	2.90	0.853
	1.08	.582	3.27							

REFERENCES

1. J. C. Simon and V. Biggi, L'Onde Elec. 332, 1, November, 1954.

2. A. S. Thomas and F. J. Zucker, 1957 IRE Nat. Conv. Record, pt. 1, p. 153; also R. L. Pease, ibid, p. 161.

3. J. T. Bolljahn, I.R.E. Trans. on Ant. and Prop. AP-9, 236 (1961).

4. C. C. Culter, Bell Telephone Lab. Rpt. MM-44-160-218 (1944).

5. W. Walkinshaw, Proc. Phys. Soc. 61, 246 (1948).

6. H. E. M. Barlow and A. E. Karbowiak, Proc. I.E.E. 101, Pt. III, 182 (1954).

7. W. Rotman, Proc. I.R.E. 39, 952 (1951).

8. L. N. Brillouin, "Wave Propagation in Periodic Structures", McGraw-Hill, 1946.

9. Mathematical Tables Project, N.B.S., "Table of Characteristic Values of Mathieu's Differential Equation", Sept. 1945.

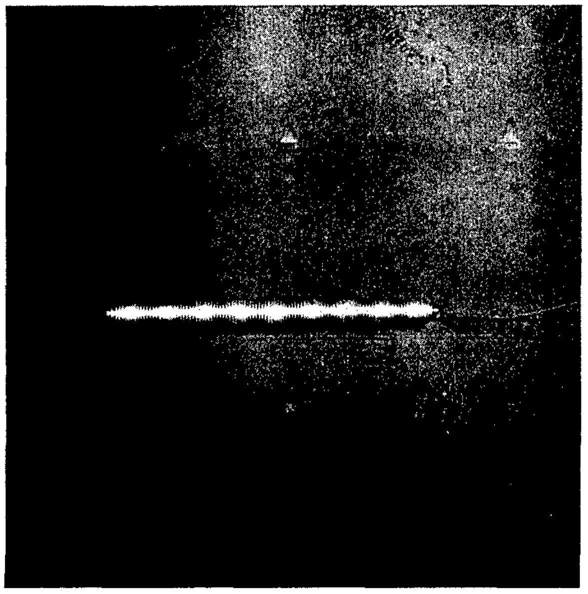

FIG. I STRUCTURE A

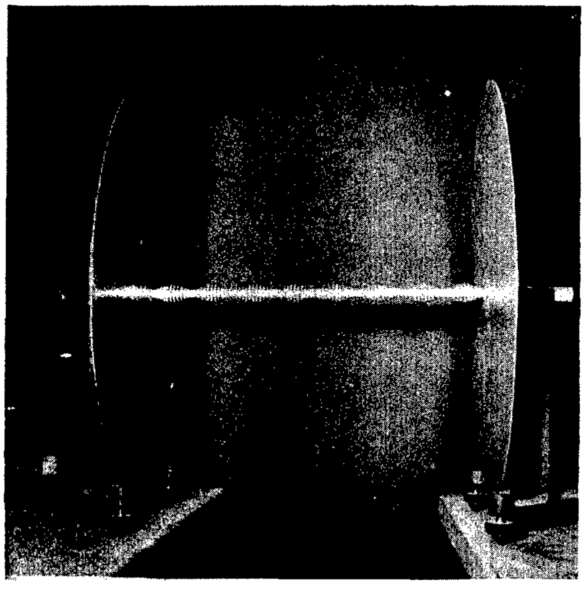

FIG. 2 STRUCTURE B MOUNTED BETWEEN REFLECTING PLATES

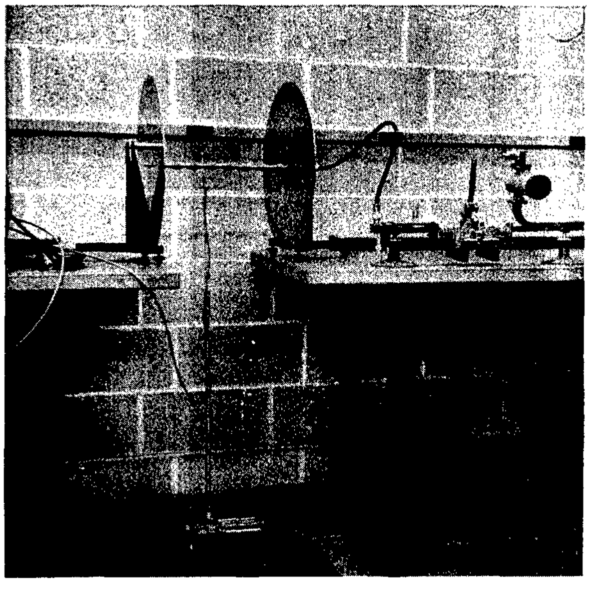

FIG. 3 WAVELENGTH MEASUREMENT, SHOWING COAXIAL FEED, PROBE, AND CARRIAGE

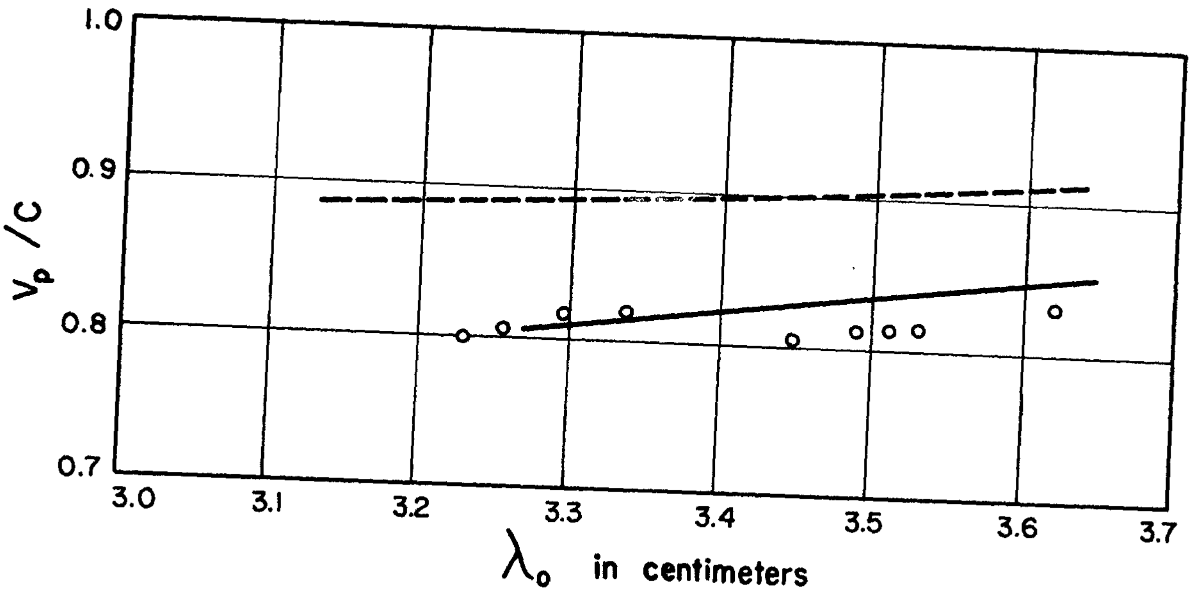

FIG. 4 (a): STRUCTURE A

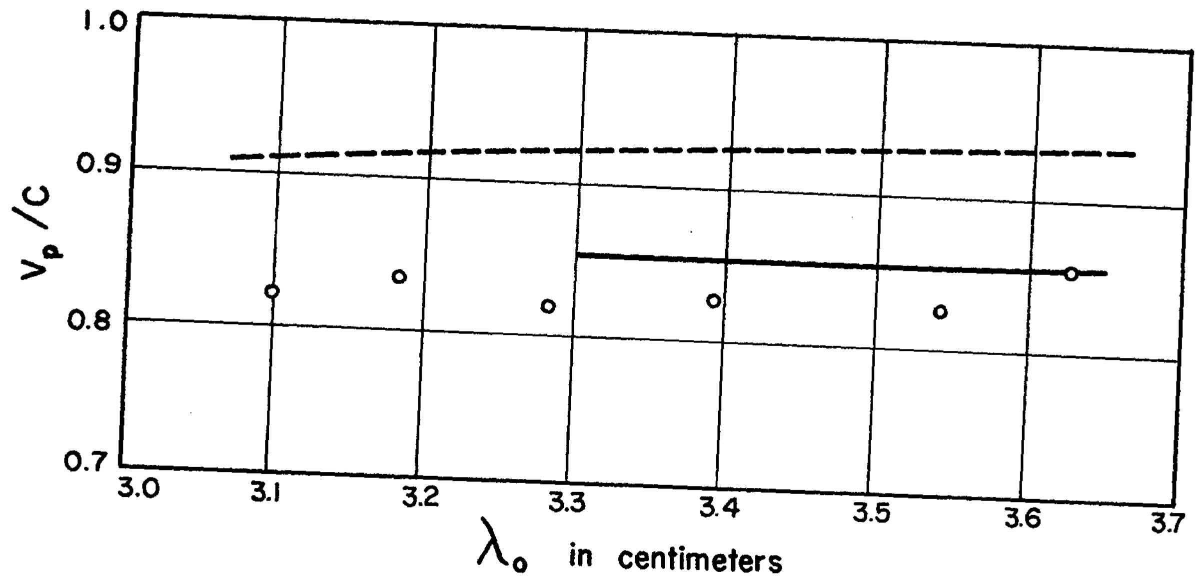

FIG. 4 (b): STRUCTURE B

FIG. 4 EXPERIMENTAL AND THEORETICAL VALUES OF PHASE VELOCITY VS. FREE SPACE WAVELENGTH FOR (a) STRUCTURE A AND (b) STRUCTURE B

o Experimental points

---- Theoretical curve for average diameters

—— Theoretical curve from Mathieu equation

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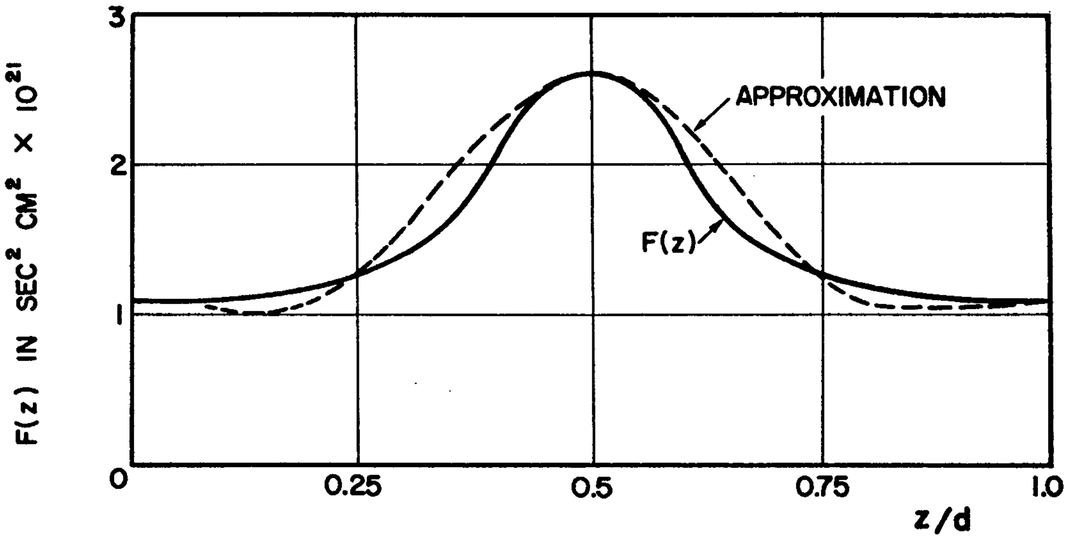

FIG. 5 F(z) VS. z/d FOR STRUCTURE B WITH λ_0= 3.625 CM AND APPROXIMATION BY THREE TERMS OF THE FOURIER SERIES

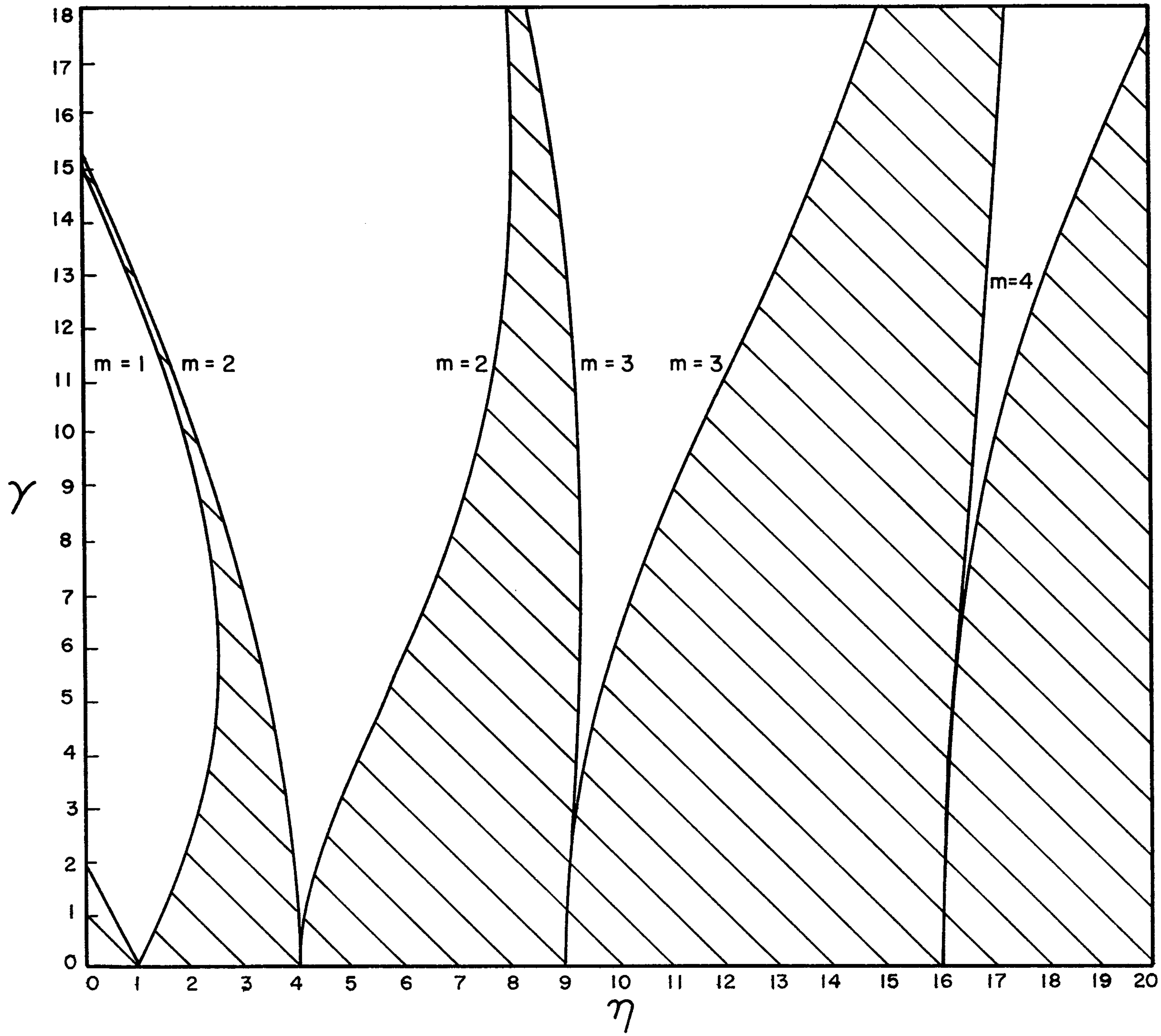

FIG. 6 CHART FOR DETERMINING CHARACTERISTIC VALUES FOR MATHIEU EQUATION

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